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On Distributed Dynamic-TDD Schemes for Base Stations with Decoupled Uplink-Downlink Transmissions

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***Abstract*—In this paper, we propose optimal distributed dynamic-time-division-duplex (D-TDD) schemes for half-duplex (HD) base stations (BSs) with decoupled uplink-downlink transmissions. In particular, for a BS with decoupled access, we propose optimal adaptive scheduling of its uplink-receptions from user 1 and downlink-transmissions to user 2 by taking into account inter-cell interference. The proposed schemes increase the uplink-downlink rate/throughput region and decrease the outage probabilities on both the uplink and downlink channels. In fact, the proposed D-TDD scheme doubles the diversity gain on both the uplink and downlink channels compared to the diversity gain of the static-TDD scheme and to the state-of-the-art D-TDD schemes for a BS with coupled uplink-downlink transmission, which results in significant performance gains.**

I. Introduction

Traditionally, a half-duplex (HD) base station (BS) operating in the time-division duplex (TDD) mode receives information on the uplink and transmits information on the downlink from/to a single user in one frequency band [1], which is known as BS with coupled access. However, recently, decoupled access has been proposed where the BS performs uplink-receptions from user 1 (U1) and downlink-transmissions to user 2 (U2) [2], [3], see Fig. 1. Similarly, a user (U3) performs downlink-receptions from BS2 and uplink-transmissions to BS3, see Fig. 1. Compared to coupled access, decoupled access, cf. Fig. 1, leads to increased coverage, and decreased outages and power consumption [2], [3]. Motivated by the promised gains of BSs with decoupled access, in this paper we investigate TDD for BSs with decoupled access.

In general, the TDD communication between the HD BS and the users can be static or dynamic. In static-TDD, a fraction of the total number of time slots is allocated for uplink-receptions and the rest of time slots are allocated for downlink-transmissions [1]. Due to the scheme being static, the time slots in which the BS performs uplink-receptions and downlink-transmissions from/to the user are prefixed and unchangeable over time [4]. On the other hand, in dynamic (D)-TDD, each time slot can be dynamically allocated either for uplink-reception or for downlink-transmission based on the instantaneous channel state information (CSI). Thereby, D-TDD schemes achieve a much better performance compared to static-TDD schemes [5], [6]. As a result, D-TDD schemes have attracted significant research interest [5]–[9].

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D-TDD schemes can be implemented in either centralized or distributed fashion [7]. In centralized D-TDD schemes, the decision for allocating the time slot for uplink-reception or for downlink-transmission is performed at a central node, which then informs the BSs about the decision. In this way, the uplink-receptions and the downlink-transmissions between neighbouring cells can be synchronized in order to minimize inter-cell interference[1] [8], [9]. However, centralized D-TDD schemes require full CSI at the central node from all links in all cells in order for the central node to make an optimal decision for allocating the time slot. In addition, the central node also needs to inform all other nodes about the scheduling decision. This requires a large amount of information to be exchanged between the central node and all other nodes. As a result, implementation of centralized D-TDD schemes, in most cases, is infeasible in practice. On the other hand, in distributed D-TDD schemes, the BS and users inside a cell allocate their uplink-receptions and downlink-transmissions without any synchronization with neighbouring cells. To this end, only local CSI is needed at the BS. As a result, distributed D-TDD schemes are much more practical for implementation than centralized D-TDD schemes.

In the literature, there is a substantial investigation of distributed D-TDD schemes for BSs with coupled access [10]–[16]. However, there are not any works which investigate distributed D-TDD schemes for BSs with decoupled access. This paper fills in this gap in the literature.

A. Related Works on Distributed D-TDD for BSs with Coupled Access

Heuristic distributed D-TDD schemes for BSs with coupled access have been proposed in [10]–[13]. In particular, [10] proposed cooperation among cells which resembles a centralized D-TDD scheme. The authors in [11] proposed a D-TDD scheme which alleviates the interference by splitting the uplink and downlink frequency. Authors in [12] and [13] investigate a distributed D-TDD scheme designed for multiple-antennas. On the other hand, optimal D-TDD schemes for BSs with coupled access have been proposed in [14]–[16]. The work in [14] proposes a coupled distributed multi-user D-TDD scheduling scheme. However, the schemes in [14] do not take into account inter-cell interference, which may lead to poor performance in practice. The authors in [15] investigated the same network as in [14], but with inter-cell interference taken into account.

[1]Inter-cell interference emerges when BSs and users in neighbouring cells transmit and receive on the same frequency band.

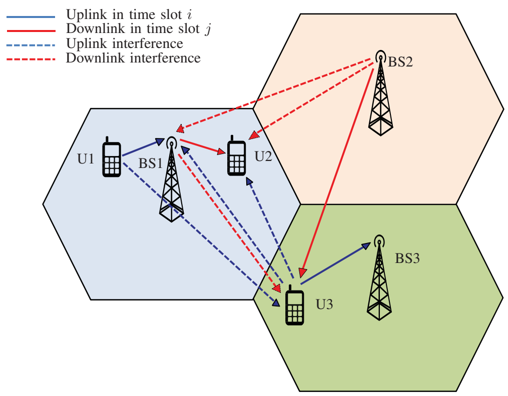

Fig. 1. System model for decoupled access comprised of half-duplex BSs and users, where $i \neq j$.

However, the solution in [15] is based on a brute-force search algorithm for allocating the time slots. Authors in [16] proposed a D-TDD scheme for performing optimal power, rate, and user allocation. However, the interference level in [16] is kept fixed during all time slots, which may not be an accurate model of inter-cell interference. In particular, in cellular networks, due to power-allocations at neighbouring BSs and due to fading, the inter-cell interference varies with time.

B. Motivation and Contribution

Motivated by the promised gains of D-TDD and of decoupled access, in this paper, we merge D-TDD with decoupled access and investigate optimal decoupled D-TDD schemes, which has not been investigated in the literature so far, to the best of our knowledge. Thereby, we propose optimal distributed D-TDD schemes for a BS with decoupled access, where the BS performs uplink-receptions from user 1 and downlink-transmissions to user 2 by taking into account inter-cell interference. The proposed schemes increase the uplink-downlink rate/throughput region and decrease the outage probabilities on both the uplink and downlink channels. In fact, the proposed D-TDD scheme doubles the diversity gain on both the uplink and downlink channels compared to the diversity gain of the static-TDD scheme and to the state-of-the-art D-TDD schemes for a BS with coupled uplink-downlink transmission, which results in significant performance gains.

II. System and Channel Models

We consider a cellular network comprised of nodes organized in cells. We assume that all nodes transmit in the same frequency band and assume transmission in N time slots. In a given time slot, a node can either receive or transmit. We divide the network into subnetworks, which consist of three nodes, and investigate optimal distributed D-TDD schemes with decoupled access for these subnetworks, where each subnetwork performs D-TDD independently of the other subnetworks but takes into account the interference from rest of the nodes in the network.

Let a considered subnetwork be comprised of nodes X, Y, and Z. Node X has data to send to node Y, while node Y has data to send to node Z. There are two instances of this subnetwork that are of interest and which will be investigated in this work:

1. Node X and node Z are user 1 (U1) and user 2 (U2), respectively, and node Y is a BS (BS1), cf. Fig. 1.

2. Nodes X and node Z are base stations BS2 and BS3, respectively, while node Y is the user, U3, cf. Fig. 1.

Since these two subnetworks become identical when the BSs and the users switch places, in the following, we only investigate the subnetworks comprised of a BS and two users.

A. Inter-Cell Interference

The BS and the downlink user, U2, are assumed to be impaired by inter-cell interference, as illustrated in Fig. 1. Let the power of the interference impairing the received signal at the BS and U2 in time slot i, referred to as the the uplink and downlink interference, be denoted by $\gamma_{IU}(i)$ and $\gamma_{ID}(i)$, respectively. Then, we can obtain $\gamma_{IU}(i)$ and $\gamma_{ID}(i)$ as

$$\gamma_{IU}(i) = \sum_{k\in\mathcal{K}} P_k(i)\gamma_{kB}(i), \tag{1}$$

$$\gamma_{ID}(i) = \sum_{k\in\mathcal{K}} P_k(i)\gamma_{k2}(i), \tag{2}$$

where $\mathcal{K}$ is the set of interfering nodes, $P_k(i)$ is the power of interfering node k, and $\gamma_{kB}(i)$ and $\gamma_{k2}(i)$ are the square of the channel gains between interfering node k and the BS and interfering node k and U2, respectively.

B. Channel Model

In the considered system we assume that the U1-BS and BS-U2 links are complex-valued additive white Gaussian noise (AWGN) channels impaired by slow fading and inter-cell interference. We assume that the transmission time is divided into $N \to \infty$ time slots. Furthermore, we assume that the fading is constant during one time slot and changes from one time slot to the next. In time slot i, let the complex-valued fading gains of U1-BS and BS-U2 channels be denoted by $h_{1B}(i)$ and $h_{B2}(i)$, respectively. Moreover, let the variances of the complex-valued AWGNs at BS and U2 be denoted by σ_B^2 and σ_2^2, respectively. For convenience, we define normalized magnitude-squared fading gains of the U1-BS and BS-U2 channels as $\gamma_{1B}(i) = |h_{1B}(i)|^2/\sigma_B^2$ and $\gamma_{B2}(i) = |h_{B2}(i)|^2/\sigma_2^2$, respectively. Furthermore, let the transmit powers of U1 and BS in time slot i be denoted by P_U and P_D, $\forall i$, respectively. As a result, the capacities of the uplink, U1-BS, channel and the downlink, BS-U2, channel in time slot i, denoted by $C_U(i)$ and $C_D(i)$, respectively, are obtained as

$$C_U(i)=\log_2\left(1+\frac{P_U\gamma_{1B}(i)}{1+\gamma_{IU}(i)}\right)=\log_2(1+P_U\gamma_U(i)), \tag{3}$$

$$C_D(i)=\log_2\left(1+\frac{P_D\gamma_{B2}(i)}{1+\gamma_{ID}(i)}\right)=\log_2(1+P_D\gamma_D(i)), \tag{4}$$

where $\gamma_U(i)$ and $\gamma_D(i)$ denote the equivalent uplink and downlink channel gains at the BS, derived as

$$\gamma_U(i) = \frac{\gamma_{1B}(i)}{1+\gamma_{IU}(i)}, \tag{5}$$

$$\gamma_D(i) = \frac{\gamma_{B2}(i)}{1+\gamma_{ID}(i)}. \tag{6}$$

III. General Scheme for Adaptive Scheduling of the Uplink-Receptions and Downlink-Transmissions of a Base Station with Decoupled Access

In this section, we formulate a general D-TDD scheme for adaptive scheduling of the uplink-receptions and downlink-transmissions of a BS with decoupled uplink-downlink transmission.

A. Problem Formulation

In a given time slot, depending on whether the BS receives from U1 in the uplink or transmits to U2 in the downlink, the considered three-node network, shown in Fig. 1, can be in one of the following three states

- *State 0:* U1 and BS are both silent.
- *State 1:* U1 transmits to BS and BS is silent.
- *State 2:* BS transmits to U2 and U1 is silent.

In order to model the three network states for time slot i, we define two binary variables $q_U(i)$ and $q_D(i)$, as

$$q_U(i) = \begin{cases} 1 & \text{if U1 transmits to BS and BS} \\ & \text{is silent in time slot } i \\ 0 & \text{otherwise,} \end{cases} \tag{7}$$

$$q_D(i) = \begin{cases} 1 & \text{if BS transmits to U2 and U1} \\ & \text{is silent in time slot } i \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

Since the considered network can be in one and only one of the three states in time slot i, the following has to hold

$$q_U(i) + q_D(i) \in \{0, 1\}, \tag{9}$$

where if $q_U(i) + q_D(i) = 0$ holds then the network is in State 0, i.e., U1 and BS are both silent in time slot i. Condition (9) results from the half-duplex constraint of the BS, i.e., the BS can either transmit or receive in a given time slot in the same frequency band.

Our task in this paper is to find the maximum uplink-downlink rates/throughputs region by selecting the optimal values $q_U(i)$ and $q_D(i)$, for $i = 1, ...N$, where $N \to \infty$. To this end, we define the following auxiliary state-selection scheme for time slot i

- $[q_U(i)=1 \text{ and } q_D(i)=0]$ if $[\Lambda_U(i) \geq \Lambda_D(i) \text{ and } \Lambda_U(i)>0]$,
- $[q_U(i)=0 \text{ and } q_D(i)=1]$ if $[\Lambda_D(i)>\Lambda_U(i) \text{ and } \Lambda_D(i)>0]$,
- $[q_U(i)=0 \text{ and } q_D(i)=0]$ if $[\Lambda_U(i) \leq 0 \text{ and } \Lambda_D(i) \leq 0]$, (10)

where $\Lambda_U(i)$ and $\Lambda_D(i)$ are decision variables which will be defined later on, cf. see (14) and (24).

IV. Uplink-Downlink Rate Region Maximization for Continuous-Rate Transmission

In this section, we assume that U1 and BS can adapt their transmission data rates in each time slot and transmit with the maximum possible data rates which do not cause outages on the underlying channels. This will allow us to obtain an upper bound on the performance of this system. In the following, we first define the uplink-downlink rate region and then propose a distributed D-TDD scheme which maximizes the rate region.

A. Rate Region

In time slot i, U1 transmits to the BS a codeword with rate $R_U(i) = C_U(i)$ and power P_U if $q_U(i) = 1$ and is silent otherwise. Similarly, the BS transmits to U2 a codeword with rate $R_D(i) = C_D(i)$ and power P_D if $q_D(i) = 1$ and is silent otherwise. Hence, the achieved rates during $N \to \infty$ time slots on the U1-BS and BS-U2 channels, denoted by $\bar{R}_k$, $k \in \{U, D\}$, respectively, are given by

$$\bar{R}_k = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} q_k(i) \log_2\left(1 + P_k \gamma_k(i)\right), k \in \{U, D\}. \tag{11}$$

The rate-pair $(\bar{R}_U, \bar{R}_D)$, given by (11), defines the boundary line of the uplink-downlink rate region. Our task in this section is to maximize the rate-pair $(\bar{R}_U, \bar{R}_D)$ and thereby obtain the maximum uplink-downlink rate region. To this end, we assume that the transmit powers P_U and P_D, although fixed during all time slots, are optimized such that the following long-term power constraints are satisfied

$$\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} q_k(i) P_k \leq \bar{P}_k, k \in \{U, D\}. \tag{12}$$

B. Problem Formulation and Solution

The maximum boundary line of the uplink-downlink rate region, $(\bar{R}_U, \bar{R}_D)$, defined by (11), can be obtained from the following optimization problem

$$\begin{aligned} & \underset{q_U(i), q_D(i), P_U, P_D}{\text{Maximize:}} \; \mu_U \bar{R}_U + \mu_D \bar{R}_D \\ & \text{Subject to :} \\ & \quad \text{C1} : q_k(i) \in \{0, 1\}, k \in \{U, D\} \\ & \quad \text{C2} : q_U(i) + q_D(i) \in \{0, 1\} \\ & \quad \text{C3} : \frac{1}{N} \sum_{i=1}^{N} q_k(i) P_k \leq \bar{P}_k, k \in \{U, D\} \\ & \quad \text{C4} : P_k \geq 0, k \in \{U, D\}, \end{aligned} \tag{13}$$

where C1 constrains the values that $q_U(i)$ and $q_D(i)$ can assume, C2 ensures that no more than one network state is active in each time slot, C3 ensures the long-term power constraints at U1 and BS are satisfied, and C4 ensures that the transmit powers $P_U(i)$ and $P_D(i)$ are non-negative. In (13), $\mu_U = \mu$ and $\mu_D = (1 - \mu)$, where μ is a constant which satisfies $0 \leq \mu \leq 1$. A specific value of μ provides one point on the boundary line of the uplink-downlink rate region $(\bar{R}_U, \bar{R}_D)$. By varying μ from zero to one, the entire boundary line of the uplink-downlink rate region $(\bar{R}_U, \bar{R}_D)$ can be obtained. The solution of problem (13) is given in the following theorem.

Theorem 1: The optimal state-selection variables $q_U(i)$ and $q_D(i)$ maximizing the uplink-downlink rate region of the considered network with continuous-rate transmission, found as the solution of (13), are given in (10), where $\Lambda_k(i)$, $k \in \{U, D\}$, are defined as

$$\Lambda_k(i) = \mu_k \log_2\left(1 + P_k \gamma_k(i)\right) - \zeta_k P_k, \tag{14}$$

where ζ_U and ζ_D are constants found such that the constraints C3 in (13) hold with equality. The optimal constant powers P_k, $k \in \{U, D\}$, are found from the following equations

$$\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \left[\frac{\mu_k q_k(i) \gamma_k(i)}{\ln(2)(1 + P_k \gamma_k(i))} - \zeta_k q_k(i) \right] = 0. \tag{15}$$

Proof: This theorem is the result of solving the optimization problem in (13), which after the relaxations $0 \leq q_k(i) \leq 1$, $k \in \{U, D\}$, and $0 \leq q_U(i) + q_D(i) \leq 1$, becomes a convex optimization problem which can be solved in a straightforward manner. Due to lack of space, the derivations are not presented in details. ■

For this scheme to operate U1, BS, and U2 have to know $\gamma_U(i)$, $(\gamma_U(i), \gamma_D(i))$, and $\gamma_D(i)$, respectively.

V. Uplink-Downlink Throughput Region Maximization for Discrete-Rate Transmission

In this section, we assume that U1 and BS do not have full CSI of their corresponding transmission links and/or have some others constraints which limit their ability to adapt the transmit rates arbitrarily in each time slot. Consequently, U1 and BS transmit their codewords with rates which are selected from discrete finite sets of date rates, denoted by $\mathcal{R}_U = \{R_U^1, R_U^2, ..., R_U^M\}$ and $\mathcal{R}_D = \{R_D^1, R_D^2, ..., R_D^L\}$, respectively, where M and L denote the total number of non-zero data rates available for transmission at U1 and BS, respectively.

A. Uplink-Downlink Throughput Region for Discrete Transmission Rates

In order to model the uplink-receptions and downlink-transmissions for discrete data rates in time slot i, we introduce the binary variables $q_U^m(i)$, $m = 1, 2..., M$ and $q_D^l(i)$, for $l = 1, ..., L$, defined as

$$q_U^m(i) = \begin{cases} 1 & \text{if U1 transmits with rate } R_U^m \text{ to} \\ & \text{BS and BS is silent in time slot } i \\ 0 & \text{otherwise,} \end{cases} \tag{16}$$

$$q_D^l(i) = \begin{cases} 1 & \text{if BS transmits with rate } R_D^l \text{ to} \\ & \text{U2 and U1 is silent in time slot } i \\ 0 & \text{otherwise.} \end{cases} \tag{17}$$

Since the considered network can be in one and only one state in time slot i, the following has to hold

$$\sum_{m=1}^{M} q_U^m(i) + \sum_{l=1}^{L} q_D^l(i) \in \{0, 1\}, \tag{18}$$

where if $\sum_{m=1}^{M} q_U^m(i) + \sum_{l=1}^{L} q_D^l(i) = 0$ holds, then U1 and BS are both silent in time slot i.

Since the available transmission rates at U1 and BS are discrete, outages can occur. An outage occurs if the data rate of the transmitted codeword is larger than the capacity of the underlying channel. To model the outages on the U1-BS and the BS-U2 links, we introduce the following auxiliary binary variables, $O_U^m(i)$, for $m = 1, ..., M$, and $O_D^l(i)$, for $l = 1, ..., L$, respectively, defined as

$$O_U^m(i) = \begin{cases} 1 & \text{if } \log_2(1 + P_U\gamma_U(i)) \geq R_U^m \\ 0 & \text{if } \log_2(1 + P_U\gamma_U(i)) < R_U^m, \end{cases} \tag{19}$$

$$O_D^l(i) = \begin{cases} 1 & \text{if } \log_2(1 + P_D\gamma_D(i)) \geq R_D^l \\ 0 & \text{if } \log_2(1 + P_D\gamma_D(i)) < R_D^l. \end{cases} \tag{20}$$

Using $O_U^m(i)$, $\forall m$, we can obtain that in time slot i a codeword transmitted by U1 with rate R_U^m can be decoded correctly at the BS if and only if (iff) $q_U^m(i)O_U^m(i) > 0$ holds. Similarly, using $O_D^l(i)$, we can obtain that in time slot i a codeword transmitted by the BS with rate R_D^l can be decoded correctly at U2 iff $q_D^l(i)O_D^l(i) > 0$ holds. Thereby, the achieved throughputs during $N \to \infty$ time slots on the U1-BS and BS-U2 channels, denoted by $\bar{R}_k$, are given by

$$\bar{R}_k = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{J} R_k^j q_k^j(i) O_k^j(i), \tag{21}$$

where $(k, j, J) \in \{(U, m, M), (D, l, L)\}$.

The throughput pair $(\bar{R}_U, \bar{R}_D)$, given by (21), represents the boundary line of the uplink-downlink throughput region. Our task now is to find the maximum boundary line of the uplink-downlink throughput region, $(\bar{R}_U, \bar{R}_D)$, by selecting the optimal values of $q_U^m(i)$, $q_D^l(i)$, $\forall m, l, i$, and selecting the optimal fixed powers at U1 and BS, P_k, $k \in \{U, D\}$, respectively, such that the following long-term power constraints are satisfied

$$\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{J} q_k^j(i) P_k \leq \bar{P}_k, \tag{22}$$

where $(k, j, J) \in \{(U, m, M), (D, l, L)\}$.

B. Problem Formulation and Solution

The maximum boundary line of the uplink-downlink throughput region, $(\bar{R}_U, \bar{R}_D)$, can be found from the following maximization problem

$$\begin{aligned} & \underset{q_U^m(i), q_D^l(i), P_U, P_D,\ \forall l,m,i.}{\text{Maximize:}} \quad \mu_U \bar{R}_U + \mu_D \bar{R}_D \\ & \text{Subject to:} \\ & \text{C1: } q_U^m(i) \in \{0, 1\}, \forall m \\ & \text{C2: } q_D^l(i) \in \{0, 1\}, \forall l \\ & \text{C3: } \sum_{m=1}^{M} q_U^m(i) + \sum_{l=1}^{L} q_D^l(i) \in \{0, 1\} \\ & \text{C4: } \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{m=1}^{M} q_U^m(i) P_U \leq \bar{P}_U, \\ & \text{C5: } \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} q_D^l(i) P_D \leq \bar{P}_D, \\ & \text{C6: } P_k \geq 0, k \in \{U, D\}. \end{aligned} \tag{23}$$

The solution of this problem is given in the following theorem.

Theorem 2: Define $q_U(i) = q_U^{m^*}(i)$ and $q_D(i) = q_D^{l^*}(i)$, respectively, where $m^* = \arg\max_m \{R_U^m\ O_U^m(i)\}$ and $l^* = \arg\max_l \{R_D^l O_D^l(i)\}$. Then, the optimal state and rate selection variables, $q_U(i)$ and $q_D(i)$, maximizing the uplink-downlink throughput region of the considered network for the case when U1 and BS transmit from finite sets of discrete transmission rates are given in (10), where $\Lambda_k(i)$, $k \in \{U, D\}$, are defined as

$$\Lambda_k(i) = \mu_k \max_j \{R_k^j O_k^j(i)\} - \zeta_k P_k, \tag{24}$$

where $(k, j) \in \{(U, m), (D, l)\}$ and the constants ζ_k, $k \in \{U, D\}$, are found such that constraints C4 and C5 in (23) hold with equality, respectively. On the other hand, the optimal fixed-powers, P_k, $k \in \{U, D\}$, are found from the following equations

$$\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \Bigg[\frac{\mu_k q_k(i)\gamma_k(i) \sum_{j=1}^{J} R_k^j \Delta_k^j(i)}{\ln(2)(1 + P_k\gamma_k(i))} - \frac{\mu_k q_k(i)\gamma_k(i) \sum_{j=1}^{J-1} R_k^j \Delta_k^{j+1}(i)}{\ln(2)(1 + P_k\gamma_k(i))} - \zeta_k q_k(i) \Bigg] = 0, \tag{25}$$

where $(k, j, J) \in \{(U, m, M), (D, l, L)\}$ and $\Delta_k^j(i)$, $(k, j) \in \{(U, m), (D, l)\}$, are defined as

$$\Delta_k^j(i) = \begin{cases} 1 \text{ if } \Big(R_k^j - \log_2(1{+}P_k\gamma_k(i-1))\Big) \\ \quad \times \Big(R_k^j - \log_2(1{+}P_k\gamma_k(i))\Big) \leq 0 \\ 0 \text{ if } \Big(R_k^j - \log_2(1{+}P_k\gamma_k(i-1))\Big) \\ \quad \times \Big(R_k^j - \log_2(1{+}P_k\gamma_k(i))\Big) > 0. \end{cases} \tag{26}$$

Proof: This theorem is the result of solving the optimization problem in (23), which after the relaxations $0 \le q_U^m(i) \le 1$ and $0 \le q_D^l(i) \le 1$, $\forall m, l$, becomes a convex optimization problem which can be solved in a straightforward manner. Due to lack of space, the derivations are not presented in details. ■

For this scheme to operate U1 and BS, have to know $\gamma_U(i)$, and $(\gamma_U(i), \gamma_D(i))$, respectively.

VI. Simulation And Numerical Results

In this section, we evaluate the performance of the proposed schemes, and then compare it to the performance achieved with a static-TDD scheme, and to the state-of-the-art D-TDD scheme for a BS with coupled uplink-downlink. To this end, we first introduce the benchmark schemes and then present the numerical results.

A. Benchmark Schemes

1) Static-TDD: In the static-TDD scheme, see [1], the BS receives and transmits in prefixed time slots. Assuming continuous-rate transmission and assuming that that the fractions of the total number of time slots, N, for uplink-receptions and downlink-transmissions are μ and $1-\mu$, receptively, e.g. uplinks occur in the first μN and downlinks in following $(1-\mu)N$ time slots, the boundary line of the achieved uplink-downlink rate region during $N \to \infty$ time slots, $(\bar{R}_U, \bar{R}_D)$, is given by

$$\bar{R}_k = \lim_{N\to\infty} \frac{\mu_k}{N} \sum_{i=1}^{N} \log_2\left(1 + \frac{\bar{P}_k}{\mu_k}\gamma_k(i)\right), k \in \{U, D\}. \quad (27)$$

On the other hand, assuming single transmission rates at U1 and BS, the boundary line of the throughput region during $N \to \infty$ time slots, is given by

$$\bar{R}_k = \lim_{N\to\infty} \frac{\mu_k}{N} \sum_{i=1}^{N} O_k^1(i) R_k^1, k \in \{U, D\}, \quad (28)$$

where $O_k^1(i)$, $k \in \{U, D\}$, are defined as

$$O_k^1(i) = \begin{cases} 1 & \text{if } \log_2\left(1 + \frac{\bar{P}_k}{\mu_k}\gamma_k(i)\right) \ge R_k^1 \\ 0 & \text{if } \log_2\left(1 + \frac{\bar{P}_k}{\mu_k}\gamma_k(i)\right) < R_k^1. \end{cases} \quad (29)$$

2) Distributed D-TDD Scheme with Coupled Uplink-Downlink: The D-TDD scheme for a BS with coupled uplink-downlink proposed in [16] is considered as a benchmark for comparison. For fair comparison, we have assumed that for the scheme in [16], the nodes can measure the CSI without errors.

B. Numerical Results

All of the presented results in this section have been performed by numerical evaluation of the derived results and are confirmed by Monte Carlo simulations. Moreover, Rayleigh fading for the U1-BS and the BS-U2 channels, and Chi-square distribution for the inter-cell interference at the BS and U2 nodes are assumed.

1) Sum-Rate: In Fig. 2, we show the sum of the uplink and downlink rates/throughputs achieved with the proposed schemes with continuous-rate transmission, with discrete-rate transmission for $M = 1$, and with the benchmark schemes as a function of the signal to interference plus noise ratio (SINR), where the SINR is defined as the ratio of the average received power and the interference power plus noise power.

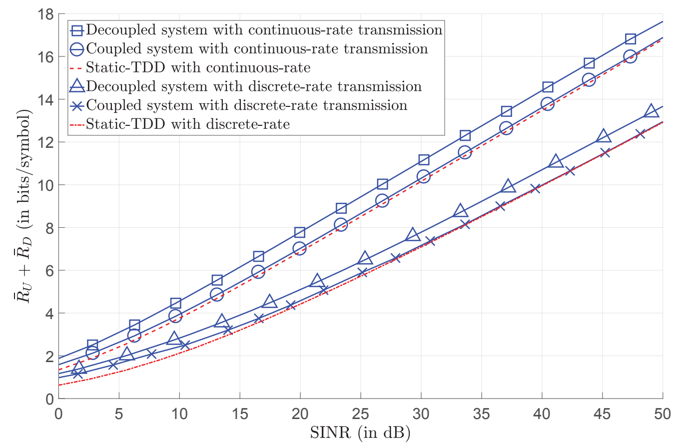

Fig. 2. Data rates/throughputs vs. SINR of the systems with decoupled access using the proposed schemes and of the benchmark scheme.

For the schemes with discrete-rate transmission the value of R is optimized numerically, for a given SINR, such that the throughput is maximized. As can be seen from Fig. 2, the performance of the proposed schemes have considerable gains compared to the benchmark schemes. Moreover, it can be seen that the decoupled system using the proposed schemes provides around 3 dB SINR gain compared to the static-TDD benchmark scheme and to the coupled system for almost the entire shown domain of the SINR. This shows that BSs with decoupled access using the proposed D-TDD schemes achieve significant performance gains compared to BSs with coupled access.

2) Rate/Throughput Region: For the example shown in Fig. 3, the mean of the channel gains of the U1-BS and BS-U2 links are calculated by the standard path-loss model as [6]

$$E\{|h_k(i)|^2\} = \left(\frac{c}{4\pi f_c}\right)^2 d_k^{-\beta}, \text{ for } k \in \{U, D\}, \quad (30)$$

where c is the speed of light, f_c is the carrier frequency, d_k is the distance between the transmitter and the receiver of link k, and β is the path loss exponent. Moreover, the carrier frequency is set to $f_c = 1.9$ GHz, and we assume $\beta = 3.6$ for the U1-BS and BS-U2 channels. In this example, the interference to noise ratio (INR) is defined as the ratio of the average received interference power and the noise power. In addition, the discrete-rates scheme has $M = L$ and $R_U^k = R_D^k = kR$, for $k = 1, 2, ..., M$, where R is optimized numerically for a given μ, such that the throughput is maximized. Also, users have omnidirectional antenna with unity gain, and the BS has a directional antenna with gain of 16 dBi. The power at U1 is set to 24 dBm and the power at BS is set to 46 dBm. The distances between U1 and BS, as well as BS and U2, are assumed to be fixed and is set to 700m. The noise figure of BS and U2 are set to 2 dB and 7 dB, respectively. The above parameters reflect the parameters used in practice [4], [6].

Using the above parameters, in Fig. 3, we demonstrate the rate region achieved with the decoupled systems using the proposed schemes for continuous-rate transmission, as well as the throughput region for discrete-rate transmission with $M = 1$. Furthermore, we show the rate/throughput regions achieved with the benchmark schemes. As can be seen from Fig. 3, the decoupled system using the proposed scheme achieves substantial gains compared to the benchmark schemes. For example, the decoupled system using the proposed continuous-rate transmission scheme has an uplink rate gain of about 16%,